A HIGH-ORDER KALMAN FILTER FOR FOCAL PLANE CALIBRATION OF NASA'S SPACE INFRARED TELESCOPE FACILITY (SIRTF)

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Extended Abstract

This paper discusses the Instrument Pointing Frame (IPF) Kalman Filter algorithm for focal plane calibration of NASA's Space Infrared Telescope Facility (SIRTF). The IPF Kalman filter is a high-order square-root iterated linearized Kalman filter, which is parametrized specifically for calibrating the SIRTF telescope focal plane and aligning the science instrument arrays with respect to the telescope boresight. The most stringent calibration requirement specifies the alignment of certain instrument pointing frames to an accuracy of 0.1 arcseconds, per-axis, 1-sigma relative to the telescope pointing frame [10]. In order to achieve this level of accuracy, the IPF filter requires 37 states to estimate desired parameters while also correcting for expected systematic errors due to: (1) optical distortions, (2) scanning mirror scale-factor and misalignment, (3) frame alignment variations due to thermomechanical distortion, and (4) gyro bias and bias-drift in all axes. The estimated pointing frames and calibration parameters are essential for supporting on-board precision pointing capability, in addition to supporting end-to-end "pixels on the sky" ground pointing reconstruction efforts.

The IPF Kalman filter design is somewhat novel in its concept to combine both science and engineering data in a completely integrated calibration formulation. For example, plate-scale parameters are estimated simultaneously with attitude calibration parameters, rather than these two problems being artificially separated and solved in separate steps (e.g., as pointed out in [9], often by different teams of scientists and engineers). Furthermore, by fitting polynomials to time-dependent behaviors, this design is able to incorporate global re-linearization of the Kalman filter (an advantage of the approach in [4], and similar to the "iterated" Kalman filter approach discussed in [5]) while still accommodating time-varying misalignments due to thermomechanical and gyro drift.

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SIRTF is a space-based telescope that will provide high-resolution views of the universe in the infrared spectrum, and represents the fourth and final element in NASA's Great Observatory program. The new space telescope is presently scheduled for launch on a Delta II in the April-May 2003 time frame. SIRTF has an 85 cm telescope aperture and uses a combination of passive cooling and liquid helium to keep its infrared instruments at temperatures of 1.4 degrees Kelvin. It will be launched into an Earth-trailing heliocentric orbit, slowly moving away from Earth with a small drift rate of about 0.1 AU per year [7]. Working in the infrared, SIRTF complements the range of science observations and wavelengths covered by the other three previous NASA Great Observatories (Chandra for X-ray, Hubble for visual, Compton GRO for gamma-rays).

SIRTF is designed to carry three science payload instruments: the Infrared Array Camera (IRAC), the Infrared Spectrograph (IRS) and the Multi-band Imaging Photometer for SIRTF (MIPS). ***IRAC*** is a general-purpose camera operating at near and mid-infrared wavelengths, which is designed to produce images 5.12 arc-min square in angular size. The images are taken simultaneously at 3.6, 4.5, 5.8 and 8.0 microns using four detector arrays of 256x256 pixels each. ***IRS*** provides high and low-resolution spectra of astrophysical objects over wavelengths of 5.3 to 40 microns. Separate modules of 128x128 pixels are available to be used for low-resolution spectroscopy in the 5.3-14 micron wavelength (Short-Low), high-resolution spectroscopy at 10-19.5 microns (Short-Hi), low-resolution at 14-40 microns (Long-Low), and high-resolution at 19-37 microns (Long-Hi). The IRS instrument includes peak-up arrays to provide real-time centroids of targeted IR objects, to facilitate their accurate transfer to the spectroscopy slits [1]. ***MIPS*** provides long wavelength imaging and large area mapping over wavelengths of 20 to 200 microns, and has some limited spectroscopy capability. For this purpose, it has three detector arrays consisting of a 128x128 pixel array for images at 24 microns, a 32x32 array for images at 70 microns and spectra from 50-100 microns, and a 2x20 array for images at 160 microns. A main distinguishing element of MIPS instrument is its scanning mirror, which moves along a single axis and is coordinated with spacecraft motions to facilitate efficient science observations.

During SIRTF's 2 month In-Orbit Checkout (IOC) and 1 month Science Verification period, the space telescope will be commanded to repeatedly perform a series of carefully designed calibration maneuvers for each science instrument array. After a maneuver series is completed for a given science array, the IPF filter processes the collected attitude history data and instrument centroid data, and produces an estimate of the instrument frame along with estimates of other alignments and calibration parameters. The basic philosophy is to combine a high-order Kalman filter with carefully designed on-orbit experiment designs to achieve the overall desired calibration accuracy. In order to meet requirements, the IPF Kalman filter has several novel and important features [3]. These features include (1) A gyro pre-processor, which allows gyro sensitivities to be pre-computed and stored beforehand. This completely eliminates the need for repeated and time-consuming gyro sensitivity propagation during each iteration of the filter cycle; (2) A parameter "masking" capability which allows the user to include in the state, arbitrary subsets of parameters. This provides a flexible parametrization which can be used to match different levels of model fidelity and science array types; (3) A formulation based on a square-root iterated linearized Kalman filter for high accuracy, good numerical conditioning [6]; (4) The flexibility to sequentially update prior estimates based on multiple data sets, where certain subsets of parameters are expected to change and not to change from one data set to another; (5) A sandwich-based experiment design concept which provides observability of all desired parameters by starting and ending on the same reference sensor [10], and allows the same calibration filter to be used for a multitude of different array types (cameras, spectroscopy slits, scanning instruments); (6) The ability to integrate both visible and infra-red sources in the same calibration data set; (7) The ability to process ''partial" centroids which only contain information along one axis of the array. This occurs, for example, when calibrating the entrance aperture of a spectroscopy slit by first scanning a source across the narrow slit width, and then along its length at a later time; (8) Operation in one of several possible "lite" modes to allow a trade-off between accuracy and robustness. For example one can invoke a completely gyroless mode on small data sets, with a minimum of required attitude history knowledge.

The IPF Kalman filter performance and all operational modes were benchmarked using simulated data produced by the IPF Filter Unit Test Environment (FLUTE) [2]. FLUTE is a unit test environment specifically designed for simulating focal plane survey maneuvers and includes all representative systematic pointing errors, and optical distortions. Based on extensive FLUTE-based testing, the IPF Kalman filter was found to meet all operational and performance requirements.

This report will discuss the IPF Kalman filter parametrization, formulation and algorithm derivation in detail, and provide an outline of the implementation. A comparison with other spacecraft calibration approaches from the literature will be given to motivate the general design philosophy [4][8][9]. Simulations will be presented demonstrating the convergence of the filter, and expected performance. The paper will conclude with a brief discussion of the focal plane survey verification process, and what is expected from actual mission data sets.

References

[1] D.S. Bayard, "Spacecraft pointing control criteria for high resolution spectroscopy," IEEE Transactions on Aerospace and Electronic Systems, Vol. 35, No. 2, pp. 637-644, April 1999.

[2] D.S. Bayard and B.H. Kang, *SIRTF Instrument Pointing Frame (IPF) Kalman Filter Unit Test Report,* JPL Internal Document D-24810, December 30, 2002.

[3] D.S. Bayard and B.H. Kang, *SIRTF Instrument Pointing Frame (IPF) Kalman Filter Algorithm,* JPL Internal Document D-24809, December 30, 2002.

[4] S. Davis and J. Lai, "Attitude sensor calibration for the Ocean Topography Experiment Satellite (TOPEX)," SPIE Space Guidance, Control and Tracking Conference, Vol. 1949, Society of Photo-Optical Instrumentation Engineers, pp. 80-91,1993.

[5] A. Gelb (Ed.), *Applied Optimal Estimation*. The MIT Press, Cambridge, Massachusetts, 1984.

[6] T.Kailath, A.H.Sayed and B.Hassibi, *Linear Estimation*. Prentice Hall,Upper Saddle River, New Jersey, 1999.

[7] T. Kia, D.S. Bayard, and F. Tolivar, "A precision pointing control system for the Space Infrared Telescope Facility (SIRTF)," Paper # AAS 97-067, 20th Annual AAS Guidance and Control Conference, Breckenridge, CO, February 5-9, 1997.

[8] M. Pittelkau, "Kalman filtering for spacecraft system alignment calibration," J. Guidance, Control and Dynamics, Vol. 24, No. 6, November-December 2001.

[9] M.D. Shuster and R.V.F. Lopes, "Parameter interference in distortion and alignment calibration," AAS Paper AAS 94-186, Feb. 1994.

[10] *Space Infrared Telescope Facility In-Orbit Checkout and Science Verification Mission Plan*, JPL Internal Document D-22622, 674-FE-301 Version 1.4, February 8, 2002.